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Jerome A. Morris

Gary A. Bishop

Donald H. Stedman

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Jerome A. Morris, Gary A. Bishop, and Donald H. Stedman*

University of Denver
Department of Chemistry and Biochemistry
Denver, CO 80208
(303) 871-2580
(303) 871-2587 fax

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P.O. Box 95085
1111 O Street, Suite 223
Lincoln, NB 68509

Executive Summary

In the winter of 1999, the University of Denver conducted a remote sensing study at Yellowstone National Park. The objective of the study was to identify the effect of oxygenated fuels on the exhaust emissions from snowmobiles. Ratios of CO, HC and toluene to CO_2 were measured and used to calculate %CO, %HC and parts per million of toluene. From the measured ratios we also calculated the grams per gallon of fuel, grams per mile and grams per kilogram of fuel for CO and HC. The ambient air temperature was collected and correlated to the remote sensing measurement to account for temperature effects.

Measurements of CO and HC were made at the West Entrance, South Entrance and west exit of Yellowstone where there were 974, 376 and 163 valid readings respectively. The mean CO exhaust emissions in percent were 6.0, 6.4 and 7.1 respectively and the medians were 6.1, 6.5 and 7.4. For CO emissions of snowmobiles the observed distribution looks normal compared to the observations from automobiles where their distribution is very skewed with most measurements low and very few high emitters. At the West Entrance where an ethanol blend was used in the snowmobiles there was a $7 \pm 4\%$ decrease, corrected for temperature, in CO emission compared to the South Entrance where non-oxygenated fuels were used. The mean HC emissions measurements in percent were 2.5 for the West Entrance, 2.2 for the South Entrance, and 2.0 at the West Exit and the medians were 2.5, 2.1 and 1.9 respectively. Since HC emissions from snowmobiles are variable with many different parameters that could not be controlled, an ethanol effect could not be clearly identified and an ethanol penalty can not be discounted.

The first ever measurement of aromatics from mobile sources in realistic operation was made at the West Entrance of Yellowstone. There were 470 valid measurements made for toluene. The mean was 1976ppm and the median was 1734ppm. The data show, on average, a correlation between higher HC emissions and higher reported toluene measurements with $r^2 = 0.93$ with an equation ppm toluene = 0.105 * ppm HC - 619.

Introduction

Remote sensing measurements are a very efficient process to measure exhaust emissions from mobile sources in route to their destination.[1] The United States Environmental Protection Agency (EPA) imposes air quality standards for several pollutants, so real-time measurements of mobile exhaust compounds are important. Real-time measurements can also be useful to determine an emission inventory for a given location.

The location chosen for study was Yellowstone National Park during the winter season. During the winter, which runs from approximately the middle of December to the beginning of March, the interior of Yellowstone is accessible predominately by snowmobiles and snowcoaches. Snowmobiles are the most popular choice for visiting the park with over 60,000 riders for the 1997-1998 winter season with a majority of the visitors renting the snowmobiles in West Yellowstone, MT. The high frequency of visitors during the winter season has led to a team effort to limit the mobile carbon monoxide emissions by promoting the use of ethanol blends in snowmobiles at West Yellowstone.

The justification for measuring the emissions of snowmobiles in Yellowstone National Park is a need to get an accurate emission measurement from winter transportation and the benefit ethanol blends have on emissions. Government officials face concerns about health and environmental impacts of these emissions in the park and a determination on how these emissions may be reduced with ethanol blended fuel is of importance.[2] Evidence that ethanol blended fuels reduce CO and HC emission is based on automobiles, which have a different combustion process.[3-6] The US EPA claims that snowmobiles are the source of “significant” air pollution in some locations and is preparing to write the first emissions standards for these machines. The new rules due September of 2000, could force manufactures to redesign or replace the two-stroke engines in these machines.[7]

Snowmobiles are almost all powered by two-stroke spark-ignited engines. The air/fuel ratio is set rich of stoichiometric to reduce peak combustion temperatures and prevent piston failure.[8] As the air/fuel ratio decreases from stoichiometric the formation of CO increases due to the decrease of oxygen (O_2). In addition, it has been shown that when the ambient temperature is decreased the emission formation of CO is also decreased because the mass of O_2 will increase for a given volume of air at lower temperatures.[9] Hydrocarbon (HC) emissions originate predominately from blow-by. This is a process in which incoming fuel mixture after the inlet port opens into the cylinder is short-circuited directly through the open exhaust port before the piston closes both ports. Blow-by is maximized at low RPM conditions and accounts for 90% of the total HC emissions. The other 10% are accounted for through flame quenching, crevice volume and at low delivery ratios where there is a large buildup of residual exhaust in the cylinder producing occasional misfires.[8] Since a majority of HC emissions is caused by short-circuit, components of gasoline such as benzene, toluene and xylenes (BTX's) will be present in the exhaust if present in the fuel. Nitric oxide (NO) is very minimal in the exhaust because the large enrichment effect contributes to lower peak combustion temperature and complete oxygen consumption, which are not optimal for NO formation.[9]

Previous emission measurements on snowmobiles were carried out on an engine dynamometer and results are consistent between the two studies with respect to CO and intake air density.[10,11] Engine dynamometer measurements of snowmobiles show a 15 – 37% increase in CO emissions in g/kW-hr with increasing intake temperature from 10 to 20°C depending on the engine manufacture and engine of the snowmobile being tested, but are still large compared to automobiles.[10] Conversion from Celsius to Fahrenheit an equation °F = (1.8 * °C) + 32 can be used. The decreased air density caused the fuel flow rate to increase and the power to decrease which increases the emission concentrations, so temperature and altitude can have a measurable effect on CO emissions irrespective the type of fuel being used. A separate study also showed evidence that an increase in temperature or altitude generated significantly higher CO emissions when tested on a dynamometer.[11] This test was done with the inlet temperature and altitude constant, but the main jet was richer than specification to simulate an altitude or temperature increase. These two sources of snowmobile emissions also have data suggesting HC emissions increasing with increasing temperature, but are still large relative to automobiles.

Additional data collected were toluene ($CH_3C_6H_5$) emissions. This is the first time that any aromatic hydrocarbon emissions have ever been measured from moving vehicles in normal operation. This type of measurement may be important in the future for oxygenated fuel studies. In the process of blending fuels to meet octane requirements, addition of ethanol (which adds octane) can be used to allow for reduced aromatic concentration. These measurements are important since mobile source contributions to the national emissions of hazardous air pollutants, which include toluene, are 41%.[12]

The main study of our fieldwork was to investigate the extent to which ethanol blended fuel decreased carbon monoxide (CO) in realistic operation and to evaluate its effect on measured hydrocarbon (HC) emissions. The addition of oxygenates to gasoline has the effect of enleaning the air/fuel mixture slightly on engines that can not adjust to optimize the air/fuel ratio. This addition of oxygen through fuel is expected to decrease CO emissions.

Experimental Design

Dr. Gary Bishop carried out preliminary feasibility study (CO and HC only) at the West Entrance in 1998 which had a successful outcome (Appendix A). During this study, the importance of temperature and altitude in two-stroke engines was not known so measurements of these were not made. The 1998 study was carried out at only one site so an altitude effect was not a concern. Temperatures fluctuated from –18 to 9°C, so it was suspected as the factor for the differences in the morning and afternoon measurements and now is known to have a measurable effect.

Since factors, such as temperature and altitude, can have an effect on CO and HC emissions it was important to design our experiment to account for these and other factors. For this study we chose to compare the exhaust emissions of snowmobiles entering Yellowstone National Park at the West Yellowstone Entrance with the snowmobiles entering the South Yellowstone Entrance. Both fleets are dominated by rental sleds with a very high percentage of the rental sleds from West Yellowstone using ethanol blended fuels while those at the South Entrance used non-oxygenated winter fuel blends and were used as the control group. The West and South Entrances have similar altitudes of 2020m and 2087m respectively and similar operating modes were present. 1 meter = 3.3 feet. Temperature was an uncontrollable factor that was not accounted for in the 1998 preliminary measurements. To rationalize the effect of temperature on the remote sensing measurements, the ambient temperature for each remote sensing emission measurement was collected at 5-minute intervals.

The main objective was to determine the extent to which the ethanol blended oxygenated fuels lowered the emissions of CO. A comparison between snowmobiles burning an ethanol blend and snowmobiles burning regular non-oxygenated fuel was performed using three different experimental methods. (1) The first experiment was to determine the %CO and HC from snowmobiles at the West Entrance and the South Entrance. Since a majority of the snowmobiles at the West Entrance are burning an ethanol blend as compared to the snowmobiles at the South Entrance; a comparison between West and South Entrance is appropriate to look for an ethanol effect on emissions. (2) In the second experiment three different individual snowmobiles were used. There was complete fuel switch over two days, non-oxygenated to ethanol. (3) The third experiment was to use two identical snowmobiles, but one using an ethanol blended fuel and the other using non-oxygenated fuel. The measurements were collected concurrently for these snowmobiles.

Three sites were used to collect data in Yellowstone for the first experiment: (1) The express entrance lane from West Yellowstone, MT (West Entrance) which is used if a park permit was purchased in advance. (2) The single exit lane located at the far north end adjacent to the express entrance for the return into West Yellowstone, MT. (3) The South Entrance via the ranger station along the Snake River from Flagg Ranch, WY. The West Entrance emission measurements are the best indication of pollutants from vehicles using ethanol blends, because most snowmobile rental agencies in West Yellowstone, MT reported using ethanol blends exclusively and at least two of the five gas stations also supplied it. Estimates of 80 – 60% of the snowmobiles are operating with ethanol blended fuel when entering Yellowstone from the West Entrance. The West Exit exhaust measurements are almost all from snowmobiles that are using a mix including a large fraction of non-oxygenate gasoline. This is because most snowmobiles entering the West Entrance go at least to Old Faithful and there need to refuel with non-oxygenated gasoline, which is the only gasoline available inside Yellowstone National Park. Measurements made at the South Entrance also represent non-oxygenated snowmobiles because most snowmobiles are rentals from Flagg Ranch or Jackson, WY where oxygenated fuel sales are limited. It is possible that 0% of the snowmobiles are using ethanol blended fuel however estimates as high as 5% of the South Entrance fleet could be using an ethanol blend. MTBE (methyl tert-butyl ether, $H_3COC_4H_9$), an oxygenated fuel additive analogous to ethanol, is not reported as being the oxygenated component in any of the oxygenated blend formulations.

In the second experiment, ethanol tests using '99 and '96 Polaris' were carried out at the South Entrance on February 14th and the non-oxygenated tests were done at the West Entrance on February 17th. The '84 Arctic Cat tests for non-oxygenated and ethanol blends were both carried out at the West Entrance on February 10th and 17th respectively. There was not a significant difference in the gradient from the West Entrance to the South so the apparent load was constant. The same drivers were used for all measurements made for a particular snowmobile and each driver tried to operate the machine the same for each emission measurement for consistency. The temperature was not constant, so the emission measurements were corrected for temperature before reporting. At least thirty valid CO and HC emission measurements were made for each snowmobile using each specific fuel.

For the third experiment, the snowmobiles used were identically equipped '99 Ski-Doo Rotax 600 Summit with DPM (digital program management). The emission measurements were made in the parking lot of the Hibernation Station, which is a lodge where ABC rentals, provider of these sleds, is located. The two snowmobiles were tested consecutively at a temperature of -2 °C and again at least thirty valid CO and HC measurements were collected for each. Different drivers were used for each snowmobile, but the same driver was used for all the measurements made for each particular snowmobile.

Instrumentation and Setup

Remote sensing is preformed with an instrument referred to as FEAT (Fuel Efficiency Automobile Test) to measure CO, CO_2, HC and toluene. FEAT is designed to emulate the results one would obtain using a conventional nondispersive infrared (NDIR) exhaust gas analyzer. The principal operation of FEAT employs a IR/UV collinear source and a detector incorporating interference filters of 4.6 μ for infrared absorption of CO, 4.3 μ for CO_2 and 3.4 μ for HC. FEAT measured the ratios of CO, HC and toluene to CO_2 which can be used to calculate units of percent, g/gal, g/mile, and g/kg. FEAT is fully described by the University of Denver in the published literature.[13, 14] The measurement methods for toluene are novel and use a high-speed UV spectrometer similar to the Popp et al. 1999 system for NO.[15] The measurements of toluene were made in the spectral absorption region of 255 – 271 nm where the absorbance of required energy needed for the electronic transitions within this molecule is strong. Even though these are the first ever measurements of toluene on a vehicle in normal operation, the detection of toluene is based on the same principle as for NO, which have been shown to be very reliable (refs).

The locations at the West Entrance and Exit for FEAT was the same as the year before, but Lane 2 was not used (Appendix A). At the South Entrance, the setup was done in the mornings approximately 45ft. beyond the stop sign at the Snake River Ranger Station with a pathlength of approximately 35ft. FEAT was setup in the same manner at the West Entrance and Exit and South Entrance as the previous year for the West Entrance and Exit. The characteristics of the snowmobiles were also the same as the previous year. West Entrance measurements were made on February 9th, 10th, 17th and 18th and South Entrance data collected on February 12th, 13th, 14th, and 15th. All of the entrance sites were chosen for data collection no more than 50ft. beyond a stop sign so interference with snow spray was minimal and the snowmobiles were in an acceleration mode. The site chosen for West Exit measurements lacked any signs to reduce snowmobile speeds. Due to this fact, snowmobiles were measured at higher speeds in a cruse mode with more snow interference than the West Entrance. For this reason valid data could only be collected for the slower moving snowmobiles (5 – 15 mph). Measurements for both entrance locations were done in the mornings between 8:00 and 12:00 p.m. except on February 10, 1999 when data were collected in the West Exit lane from 1:00 until 4:00 p.m.

Temperature measurements were gathered by means of a Davis weather station, The Weather Wizard II (Davis Instruments, Hayward, CA) at each respective site.

Data Analysis and Results

Data were collected between February 9 – February 18, 1999 with a majority of the measurements coming from the high volume West Entrance. 974 valid CO/CO_2 and HC/CO_2 data were accumulated for the West Entrance. 470 valid toluene/CO_2 measurements were also collected at the West Entrance during the last two days, which were the only times we attempted to measure toluene. At the South Entrance, 381 valid CO/CO_2 and HC/CO_2 measurements were collected and at the west exit there were 163. For the purpose of reporting, the ratios of CO/CO_2 and HC/CO_2 can be converted to percent, which would be measured by a tailpipe probe, grams/gallon, grams/mile and grams/kilogram of fuel for CO and HC. The ratios are converted to percent using a combustion equation in previous literature.[13] This equation was modified for the combustion of 8% ethanol and applied to West Entrance data to correct for the addition of oxygen.[3] The conversions to g/gal, g/mile, and g/kg fuel were achieved using the following equations:

(1) $((CO/CO_2)(0.86 \text{ g carbon/g fuel})(28 \text{ g CO/mole})(726\text{g fuel/L})(3.88\text{L/gallon})) / ((1+CO/CO_2+3{*}HC/CO_2)(12 \text{ g carbon/mole})) = \textit{x grams CO/gallon}$

(2) (x grams CO/gallon) / (9 – 15 miles/gallon) = *x grams CO/mile*

(3) $((CO/CO_2)(0.86 \text{ g carbon/g fuel})(28 \text{ g CO/mole})) / ((1+CO/CO_2+3{*}HC/CO_2)(12 \text{ g carbon/mole})) = \textit{x grams CO/kilogram of fuel}$

The same equations are used for the calculation of g HC/gal and g HC/kilogram fuel except the molecular weight of propane (44 g/mole) is used since we report HC as propane and the HC/CO_2 ratio replaces the CO/CO_2 ratio in the numerator. In equation 2, grams HC/mile can be calculated by replacing grams CO/gallon with grams HC/gallon also in the numerator.

I. Method 1

The first experiment was to measure the CO and HC emissions at the West and South Entrance and identify an ethanol effect. Distributions of %CO and %HC were compared for these two entrances along with a comparison of %CO and %HC vs. temperature. A correlation of CO and HC to the ambient temperature has been very important in the process of quantifying the ethanol effect.

Table 1 is the summary of the emissions from the West Entrance, West Exit, and South Entrance. Percent CO and HC have been converted to g/gal and g/mile for later comparison to other mobile source emissions.

Figure 1 shows a distribution of a percentage of the measured fleet vs. the % carbon monoxide binned from 1 to 13% for data collected at the West and South Entrances. The upper limit of each bin is defined as ≤ %CO. The distribution is approximately normal with the median within 3% of the mean for both West and South Entrances. The mean %CO results for West and South were 6.0 ± 0.1 and 6.4 ± 0.2 % and median was 6.1 and 6.5% respectively. The error is the standard error of the mean.

Figure 2 is a percentage of the measured snowmobile fleet vs. the distribution of %hydrocarbons for the West and South Entrances. The West Entrance has a larger percent of its snowmobile fleet > 2.5% than at South. The means are 2.5 and 2.2% respectively. The medians are 2.5 and 2.1% respectively and the distribution looks closer to normal than a fleet of automobiles that are very skewed.[16]

Location of Measurements (# of valid data)	**Mean %CO (Median)**	**Mean %HC (Median)**	**g CO/gal[1] (g CO/mile)[2]**	**g HC/gal[1] (g HC/mile)[2]**
West Entrance (974)	6.0 (6.1)	2.5 (2.5)	1344[3] (149 – 90)	890[3] (99 – 59)
West Exit (163)	7.1 (7.4)	2.0 (1.9)	1695[4] (188 – 113)	739[4] (82 – 49)
South Entrance (376)	6.4 (6.5)	2.2 (2.1)	1492[4] (166 – 99)	817[4] (91 – 54)

[1]Calculated assuming a fuel density of 726 g/L.
[2]Calcualted assuming a fuel consumption range of 9 to 15 mpg.
[3]Assuming a carbon wt. of 83% for ethanol blended fuel.
[4]Assuming a carbon wt. of 86% for non-oxygenated fuel.

Table 1. Emissions calculated from valid CO/CO_2 & HC/CO_2 measurements along with location.

The emissions from CO and HC from the West and South Entrances should reflect an ethanol effect if all other variables are the same, but that is not the case. The temperature of the ambient air was not the same for all measurements. Decreasing temperature is thought to lower CO emission since $[O_2]$ increases. In addition to the measured CO and HC measurements, the temperature of the ambient air was also recorded and correlated to their emissions. Figures 3 and 4 show the measured CO and HC emissions binned by temperature range. In Figure 3, measured CO emissions decrease with decreasing temperature for both West and South Entrances. At the South Entrance, non-oxygenated fuel operation, it is apparent that CO emissions from snowmobiles are higher at South than West at all temperatures from –15 to 5 °C. It is evident that CO emissions are influenced by the intake air temperature of snowmobiles in such a way that the CO emissions decrease with decreasing temperature. The temperature effect on CO emission at the West and South Entrances was an 8 ± 4% emission decrease for both from 258-273K. The equation from Figure 3 is $y = 0.034 \pm 0.002x - 3.20$.

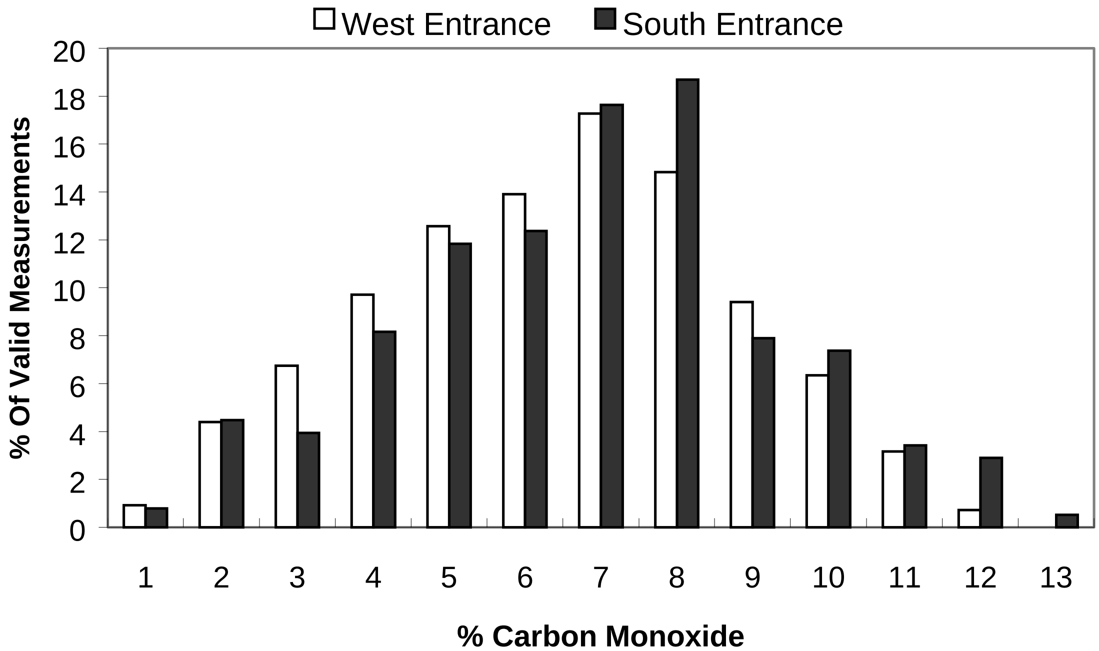

Figure 1. Histogram comparison of remote sensing data from West and South Entrances of carbon monoxide emissions from snowmobiles. Means are 6.0 ± 0.1 and 6.4 ± 0.2% respectively. The standard error of the mean is used to report the error, where N=974 for the West and N=376 for the South Entrance. The upper limit of each bin is defined as ≤ the concentration.

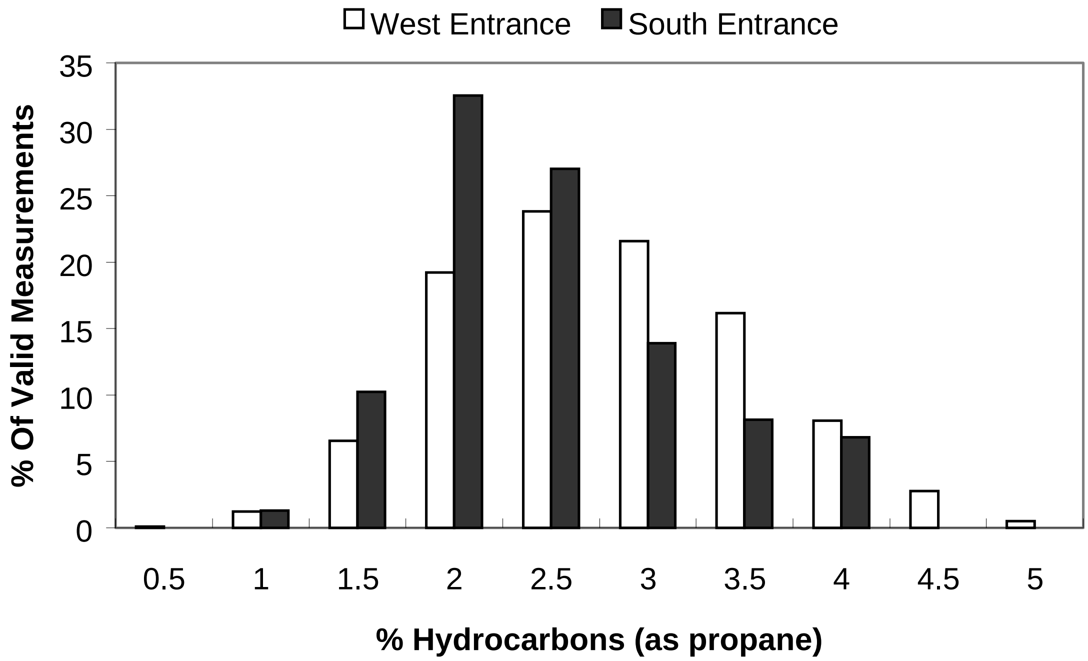

Figure 2. Histogram comparison of remote sensing data from West and South Entrances of hydrocarbons (as propane) emissions from snowmobiles. Means are 2.53 ± 0.02 and 2.20 ± 0.04% respectively. The standard error of the mean is used to report the error. The upper limit of each bin is defined as ≤ the %HC.

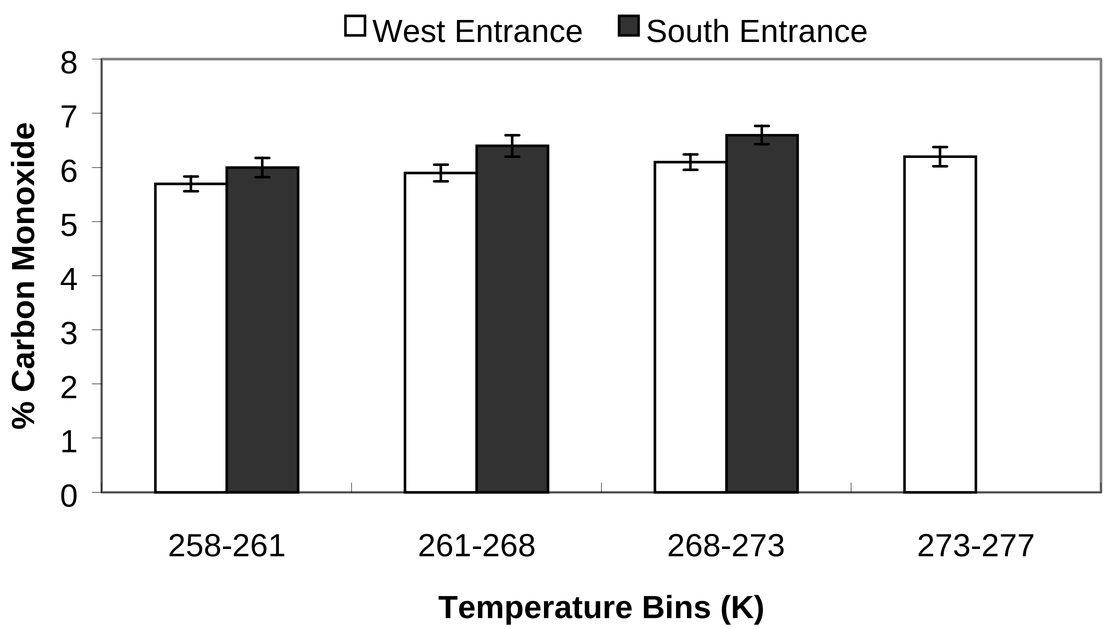

Figure 3. The temperature effect on the measured emission of carbon monoxide at the West and South Entrances. The error bars represent the standard error of the mean. The upper limit of each bin is defined as ≤ the temperature. Kelvin = 273.15 + °C

The lower CO emissions at the West Entrance than at the South for any given temperature points to an ethanol effect that are decreasing the mean CO emissions. Statistics were performed on the CO emission from the West and South Entrances, which shows that the vehicles entering at the South Entrance would have achieved 7 ± 4 % decrease (±95% confidence interval) in CO emissions, corrected for temperature had they been using ethanol blends equivalent to those used at the West Entrance.

In Figure 4, a correlation between measured %HC and temperature was also done to identify any temperature effect. The main source of HC emission in snowmobiles is from blow-by so the effect of temperature is not a combustion issue, but the amount of blow-by.

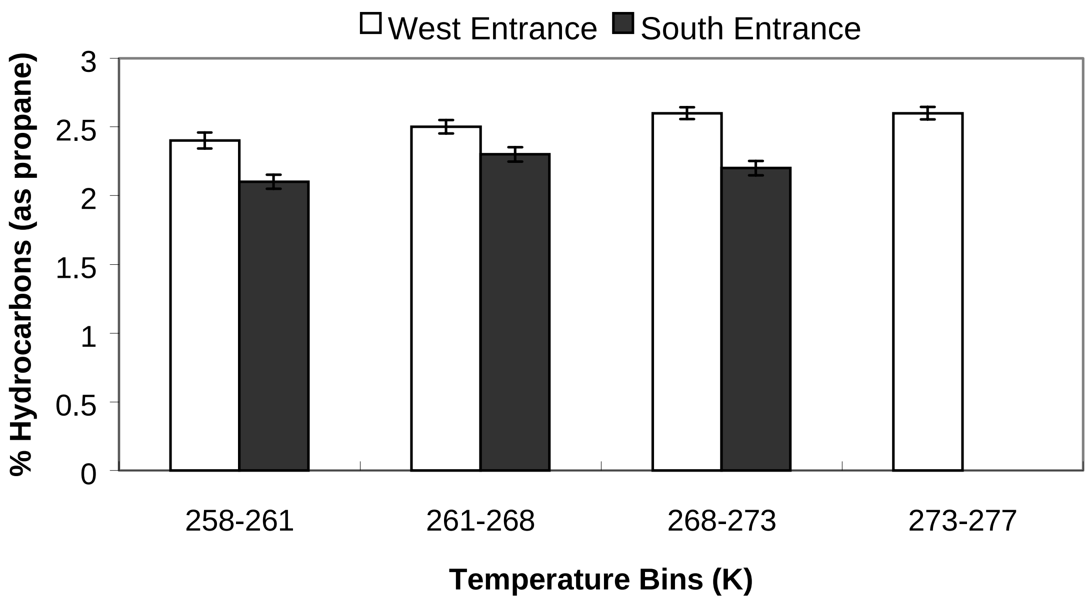

Figure 4. The temperature effect on measured hydrocarbon emissions for snowmobiles at the West and South Entrances. The error bars represent the standard error of the mean. The upper limit of each bin is defined as ≤ the temperature. Kelvin = 273.15 + °C

Since blow-by is the major source of HC emissions, the type of fuel may not be the only reason for the differences in HC emissions between the West and South Entrance. One possible reason for the difference in the HC emissions is because ethyl alcohol (ethanol) absorbs light in the same wavelength region as propane therefore increasing the signal as compared to non-oxygenated fuels.[17] Another difference may be explained by the warm snowmobile theory: The warmer the snowmobile, the less resistance from the drive train which should decrease the fuel rate and limit the amount of blow-by. The South Entrance is located 2.5 miles from Flagg Ranch, which is the paved road limit for all other vehicles, so the snowmobiles are driven a few miles at 35-45 mph before their emissions are measured. At the West Entrance the maximum posted speed is 20 mph and the entrance is < 0.5 miles from the town of West Yellowstone. Since HC emissions in two-stroke engines scale with power demand the observed HC emissions can be variable. This could explain the higher HC emissions at West because of the increased in power needed which leads to increased fuel rate. Another power factor is that ethanol blended fuels have 3-4% less energy content than non-oxygenated fuels. These effects suggest that HC measurements may be higher for the ethanol blend location due to the spectroscopic technique for data collection and uncontrolled snowmobile power requirement parameters rather than the addition of oxygen to the fuel.

Afternoon measurements for CO and HC were only collected on February 10 at the West Exit. There were 163 valid measurements for both CO and HC and the average temperature was -6 °C. The temperature remained constant from 8:00am to 5:00pm with only a 3 °C change from early morning to late afternoon. Afternoon measurements started at 1:00pm where data were collected at the West Exit. There was a difference in the driving mode at the exit where they were now in a cruise mode instead of the acceleration mode at the entrance. The snowmobile operating temperatures were also considerably hotter than when tested in the morning.

The average valid %CO and %HC emissions in the afternoon were 7.1 and 2.0 respectively and morning measurements were 5.8 and 2.5. This is an 18% increase in CO and 20% decrease in HC from the morning to the afternoon. Fuels can explain 7% of the difference in CO emissions, since the only fuel to buy inside the park in non-oxygenated. The ambient temperature did not significantly change, so the difference may not be in the ambient temperature but rather the inlet air temperature. The longer a snowmobile runs the hotter its crankcase so the inlet temperature in the cylinder may be significantly higher in the afternoon than in the mornings. The operation mode is also a factor, but how much is hard to quantify. A combination of different fuel, warmer operation temperatures and driving mode most likely accounts for the changes in %CO and %HC from the morning to the afternoon.

Previous work has been shown from engine dynamometer studies that the addition of oxygenated fuel definitely reduces the CO emissions. Effects on HC emissions were equivocal. Table 2 is a comparison of the results from an engine dynamometer study and the results from remote sensing in Yellowstone. It should be noted that the dynamometer studies are done with ambient temperatures of 20 °C and with engines at fully operational temperatures. Conversion have been made to grams of CO and HC / kilogram of fuel for comparison purposes.

The dynamometer tests employ two different dynamometers: (1) eddy-current dynamometer and (2) water-brake dynamometer. The eddy-current dynamometer results are from a five-mode test cycle using a 440-cc liquid cooled Arctco engine. The results from water-brake dynamometer are also from a five-mode test cycle but is evaluated with a 488-cc Polaris engine. The Polaris engine was air-cooled.

Type of Measurement (fuel type or location)	**g CO / kg fuel**	**g HC / kg fuel**
Remote-sensing[1] (West Entrance-ethanol)	489	312
Remote-sensing[2] (South Entrance-nonoxy)	543	297
Remote-sensing[2] (West Exit-nonoxy)	617	267
Eddy-current Dynamometer (oxygenated fuel)	665	319
Eddy-current Dynamometer (non-oxygenated fuel)	727	312
Water-brake Dynamometer (oxygenated fuel)	834	271
Water-brake Dynamometer (non-oxygenated fuel)	872	315

[1]Calculated assuming a carbon wt. of 86% for non-oxygenated fuel.
[2]Calculated assuming a carbon wt. of 83% for ethanol blended fuel.

Table 2. A comparison of emissions from remote sensing studies and engine dynamometer studies.

It is evident that oxygenated fuel lowers the CO emissions in both the remote sensing and the engine dynamometer studies. The HC emissions are variable and there is not a consistent correlation when oxygenated fuels are being used. Comparisons to single snowmobile/engine results may not be relevant to a fleet of snowmobiles because of the variability from one snowmobile to the next, shown in Figures 1 and 2. This is an advantage of using remote sensing as the technique for emission measurement because distributions of realistic fleets are easier to obtain in contrast to single snowmobile/engine dynamometer tests. Differences also arise between remote sensing and dynamometer tests because dynamometer tests are emissions over a 5 mode driving cycle and remote sensing measurements are essentially the emissions from one of the those modes.

II. Method 2

Despite the fact that individual snowmobiles/engine measurements suffer from an inevitable large variability between one snowmobile/engine and the rest, we did carry out two fuel switching experiments (Appendix C). Three different snowmobiles were used and two different fuels for the emission data. The snowmobiles are as follows: (1) 1999 Polaris Sport, (2) 1996 Polaris Lite GT, (3) 1984 Arctic Cat Panther. At least thirty drive-by emission measurements were collected for each snowmobile using 10% ethanol fuel and for non-oxygenated fuel to investigate any effect of ethanol. The temperature varied from –8 to 1°C depending on the measurements being made, so the data were corrected for temperature before reporting, using equations for temperature effect which were derived from Figures 3 and 4. The equations from Figures 3 and 4 are $y = 0.034 \pm 0.002x - 3.20$ and $y = 0.014 \pm 0.004x - 1.38$ respectively. Table 3 summarizes the results from the following experiment.

As the results suggest in Table 3, the '99 Polaris Sport and the '96 Polaris Lite GT have an inverse effect of what was expected. The '84 Arctic Cat did follow the trend expected with a decrease in %CO with the use of an ethanol blend. These results are not entirely surprising since the CO and HC distributions in the earlier figures show very large intrinsic variability. Individual snowmobile emissions are also very variable with many parameters controlled. Ethanol effects of these few snowmobiles are not close to fleet average effects with the newer snowmobiles apparently having an opposite effect. Method 2, individual snowmobile measurements, is probably not a suitable test for a comparison to a fleet of snowmobiles, but is representative of the variability of individual measurements of an individual snowmobile.

	% Carbon Monoxide		**% Hydrocarbons**	
	10% ethanol	non-oxygenated	10% ethanol	non-oxygenated
'99 Polaris Sport	6.9 ± 0.2	5.9 ± 0.2	1.7 ± 0.1	1.3 ± 0.1
'96 Polaris Lite	6.7 ± 0.2	6.3 ± 0.3	1.5 ± 0.1	1.5 ± 0.1
'84 Arctic Cat Panther	7.4 ± 0.1	10.0 ± 0.2	1.3 ± 0.1	2.2 ± 0.1

Table 3. Summary of valid CO and HC emission measurements, corrected for temperature, made for three different snowmobiles using 10% ethanol and again for non-oxygenated fuel. The respective error is the standard error of the mean.

III. Method 3

The last experimental method used to identify an ethanol blend effect was to use two identical snowmobiles, one operating on 10% ethanol and the other with non-oxygenated fuel (Appendix D). The results are summarized in Table 4 and an apparent ethanol effect is present for CO emissions. The Ski-Doo operating with an ethanol blend has 11 ± 3% lower percent carbon monoxide emissions when compared to the snowmobile running on non-oxygenated fuel. For hydrocarbons there is no significant difference since the error overlaps the mean measurements.

	% Carbon Monoxide	**%Hydrocarbons**
'99 Ski-Doo 600 (A) (ethanol)	6.7 ± 0.2	2.0 ± 0.1
'99 Ski-Doo 600 (B) (non-oxygenated)	7.5 ± 0.2	2.2 ± 0.1

Table 4. Summary of valid CO and HC average emission measurements collected for two identical snowmobiles, one operating on 10% ethanol and the other on non-oxygenated fuel.

IV. Additional Measurements

In addition to CO and HC data collection, a preliminary experiment including real-time toluene measurements was performed the last two days simultaneously with measurements of CO and HC for snowmobiles. Figure 5 is the distribution of valid toluene concentrations in parts per million at the West Entrance, which was the only location where data were gathered for toluene. The mean and median were 1976 ppm and 1734 ppm, respectively.

Toluene measurements for a mobile emission source in realistic operation have never been accomplished with any form of remote sensing before this study. The relative toluene to hydrocarbon average ratio in our measurements is consistent with the toluene content of typical non-oxygenated gasoline.[18] This is expected since most of the hydrocarbons are emitted from blow-by. Figure 6 shows a correlation between the average toluene and average HC emissions in parts per million. The concentrations of toluene were sorted from lowest to highest and binned into 19 equal groups and averaged. On the whole, as the average toluene emissions increased, so did the HC. This should be the observed effects since a majority of the HC emissions are raw gasoline in which toluene is one of its largest single components by weight. This correlation resulted an equation of ppm toluene = (0.105 ± 0.003) * ppm HC – 619 for the line with a $r^2 = 0.93$.

Further calculations, a molar ratio (slope) of 0.105 toluene/HC can be converted to a mass ratio of toluene/HC of 10.5 ± 1.0%. In a GC study of Denver gasoline blended with ethanol the mass percent of toluene was 12.8%. This indicates that the hydrocarbons exiting the exhaust may be largely due to the process of blow-by in the cylinder and not from other combustion processes.

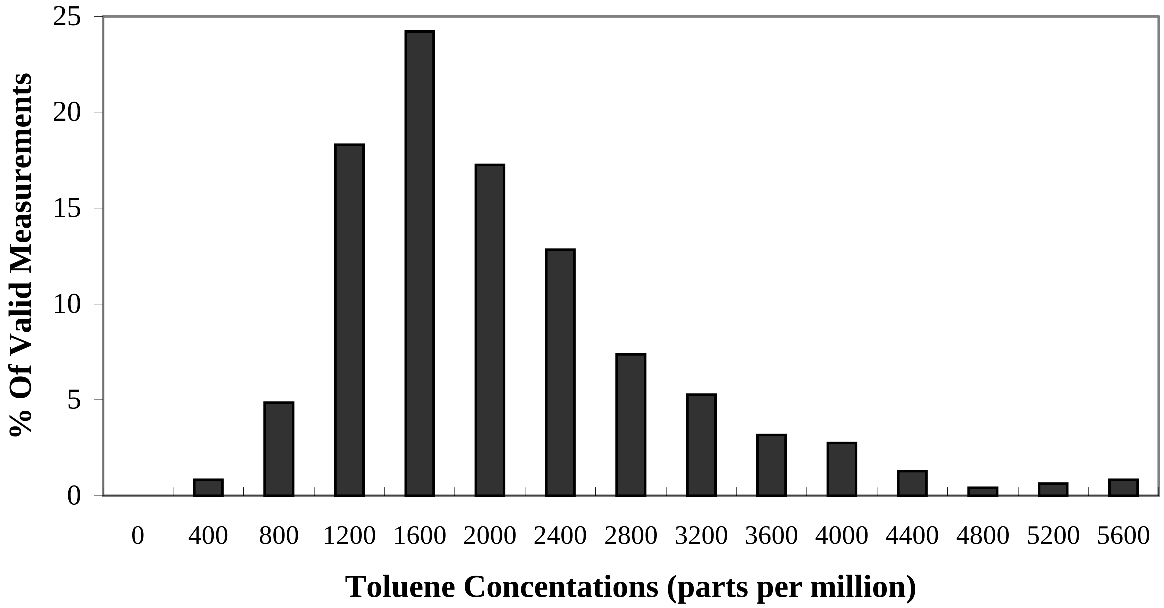

Figure 5. The distribution of measured toluene emissions at the West Entrance of Yellowstone. The upper limits of each bin ≤ the concentration.

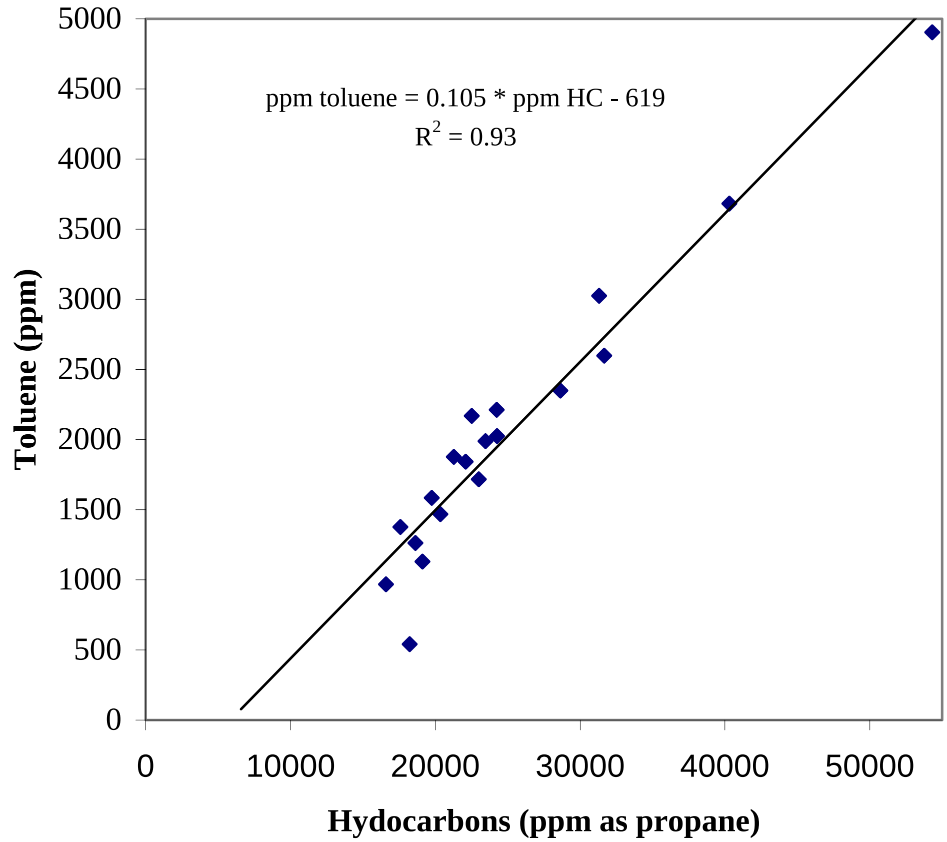

Figure 6. A correlation of average emissions of toluene vs. HC in parts per million for snowmobiles in Yellowstone.

Summary and Conclusion

The University of Denver was successful in measuring the concentrations of carbon monoxide, hydrocarbons, and toluene in snowmobile emissions. The main research was to identify the effect on fleet average emissions when 8% ethanol was used in the fuel blend. In the first experiment for the comparison at the West and South Entrances there is an obvious difference between the emissions for %CO. After correction for temperature we show that the CO emission at the South Entrance would be reduced by $7 \pm 4\%$, with 95% confidence had those snowmobiles been using ethanol blends. This is approximately 1% decrease in CO emissions per 1% of ethanol blended in the fuel formulations. Dynamometer studies also show CO emissions being reduced 4 – 9% in g/kg when 10% oxygenated fuels were used as the combustion source. Dynamometer studies and our data do not show significant effects on HC emissions, but the HC emissions are approximately sixty times greater than automobiles if compared to the Denver, CO fleet.[19]

Toluene emissions were additional measurements that were made in the process of measuring CO and HC. These measurements are important because if ethanol is blended with a lower aromatic fuel the toluene emissions, along with benzene and xylene, will be reduced. The toluene measurements that were collected at the West Entrance of Yellowstone show a similar percent of toluene in the exhaust as compared by GC analyses of typical gasoline indicating that blow-by is a large source of hydrocarbons. These toluene emissions are the first real-time remote sensing measurements of any aromatic hydrocarbon reported for any mobile source emitter.

References

1. Calvert, J.G.; Heywood, J.B.; Sawyer, R.F; Seinfeld, J.H. "Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions" *Science*, **1993**, *261*, 37-45.

2. National Park Service. 1995. *Ambient Air Quality Study Results-West Entrance Station*, Yellowstone National Park, winter **1995**.

3. Bishop, G.A.; Stedman, D.H. "On-Road Carbon Monoxide Emission Measurement Comparisons for 1988-1989 Colorado Oxy-Fuels Program" *Environmental Science & Technology*, **1990**, 24, 843-847.

4. "Regression Modeling of Oxyfuel Effects on Ambient CO Concentrations", *Systems Application International, Inc.*, January 8, **1997**.

5. Kirchstetter, T.W.; Singer, B.C.; Harley, R.A.; Kendal, G.R.; Chan, W. "Impact of Oxygenated Gasoline Use On California Light-duty Vehicle Emission" *Environmental Science & Technology*, **1996**, 30, 661-670.

6. PRC Environmental, Inc. *Performance Audit of Colorado's Oxygenated Fuels Program*, Final Report to the Colorado State Auditor Legislative Services, Denver, CO, **1992**.

7. http://www.epa.gov/oppeoee1/globalwarming/news/greenwire/a021999_1.html.

8. Nuti, M.P. *Emissions from Two-Stroke Engines.* Society of Automobile Engineers, Inc.: Warrendale, PA, **1998**.

9. Heywood, J.B. *Internal Combustion Engine Fundamentals.* McGraw-Hill: New York, **1998**.

10. Wright, C.W.; White, J.J. "Development and Validation of a Snowmobile Engine Emission Test Procedure" *Society of Automobile Engineers 982017*, **1998**.

11. White, J.J.; Carroll, J.N.; Haines, H.E. "Emissions from Snowmobile Engines Using Bio-Based Fuels and Lubricants" *Society of Automobile Engineers 972108*, **1997**.

12. United States Environmental Protection Agency. *National Air Quality and Emission Trends Report, 1997*, EPA 454-R-98-016 December **1998**.

13. Bishop, G.A.; Stedman, D.H. "Measuring the Emissions of Passing Cars" *Accounts of Chemical Research*, **1996**, 29, 489.

14. Bishop, G.A.; Stedman, D.H. “Automobile Emissions On-Road” *The Encyclopedia of Environmental Analysis and Remediation*, **1998**, 1, 542-555.

15. Popp, P.J.; Bishop, G.A.; Stedman, D.H. “Development of a High-Speed Ultraviolet Spectrometer for Remote Sensing of Mobile Source Nitric Oxide Emissions” *Journal of the Air &Waste Management Association*, Accepted for publication.

16. Zhang, Y.; Stedman, D.H.; Bishop, G.A.; Beaton, S.P.; Guenther, P.L.; McVey, I.F. “Enhancement of Remote Sensing for Mobile Source Nitric Oxide” *Journal of the Air & Waste Management Association*, **1996**, 46, 25-29.

17. Singer, B.C.; Harley, R.A.; Littlejohn, D; Ho, J.; Vo, T. “Scaling of Infrared Remote Sensor Hydrocarbon Measurements for Motor Vehicle Emission Inventory Calculations” *Environmental Science & Technology*, **1998**, 32, 3241-3248.

18. Desert Research Institute. *Real-world Automotive Emissions-Results of Studies in the Fort McHenry and Tuscarora Mountain Tunnels*. DRI Document No. 6480-1D1. March **1994**.

19. Stedman, D.H.; Bishop, G.A.; Aldrete, P.; Slott, R.S. “Repair Avoidance and Evaluating Inspection and Maintenance Programs” *Environmental Science & Technology*, **1998**, 32, 1544-1545.

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Appendix A:

1998 Preliminary Snowmobile Emission Survey in Yellowstone National Park

Final Report

1998 Preliminary Snowmobile Emission Survey in Yellowstone National Park

prepared by:

Gary A. Bishop and Donald H. Stedman
Department of Chemistry and Biochemistry
University of Denver
Denver, CO. 80208

December 1998

Introduction

During Yellowstone's winter season, which runs from mid-December to the first of March, the interior areas of the parks are only accessible to the public by foot (snowshoes/skis), snow coaches and snowmobiles. Snowmobiles are a very popular choice for exploring the park and as such large numbers of visitors rent snowmobiles to visit the park during this time. The University of Denver was invited by the National Park Service to conduct an emission survey of in-use snowmobiles (sleds) at the West Yellowstone entrance to Yellowstone National Park during February 1998.

Utilizing an infra-red remote sensor (FEAT, Fuel Efficiency Automobile Test), originally designed to measure carbon monoxide (CO) and hydrocarbon (HC) emissions of light-duty motor vehicles, measurements were carried out between February 26 - March 1, 1998 at the West Yellowstone park entrance (1). The majority of the sleds measured at this location were rented in the West Yellowstone area.

Experimental

The entrance to the park from the town of West Yellowstone, MT. is divided into three single lane entrances with attendant booths located on the left side of each lane. The FEAT was setup in the mornings approximately 20 ft. beyond the entrance booth on a slight uphill incline to measure the sleds as they were entering the park. This location was chosen to minimize the amount of snow spray that the sleds would entrail. Two changes were made to the standard operating procedure, the source and detector were placed atop the snow on insulating pads and the infra-red sensing beam was lowered to about 6 inches above the snow. The beam height was lowered to better sample the nearly snow level exhaust plumes which snowmobiles leave behind. Lane 3 (numbered from south to north) is the primary entrance lane from W. Yellowstone (the express lane for prepurchased passes which are predominately rental sleds) and was used for data collection on the mornings of 2/26 - 2/28. Lane 2 was used on the final morning (3/1/98) to attempt measurements on the small number of snow coaches which enter the park. Data were collected in the morning between the hours of 7:30 and 12:00 am.

The afternoon measurements were all attempted on the single exit lane located at the far north end of entrance gate. The morning measurements were made at speeds between 5 - 15 mph with operating rpm levels of 4000 - 7000 rpm's. The afternoon measurements were attempted over a much larger range of speeds but with similar operating rpm's. It should be noted that successful afternoon measurements were only accomplished on the slow moving (5 - 15 mph) sleds due to interferences caused by snow spray at the higher speeds. Afternoon measurements were collected between 2:00 and 5:00 pm.

Results / Discussion

Tables 1 and 2 summarizes all of the measurements. Table 2 reviews a subset of the data where both the carbon monoxide (CO) and hydrocarbon (HC) measurement had valid data flags. Gram per gallon values have been calculated assuming a fuel density of 0.726 g/ml

Table I. Summary of Measurement Activity.

Date	NPS Snowmobile Entrance Count[1]	Measurement Attempts (Entrance/Exit)	Valid CO Measurements	Valid CO & HC Measurements
2/26/98	530	451 (219/232)	347 (208/139)	308 (194/114)
2/27/98	633	373 (313/60)	332 (283/49)	308 (264/44)
2/28/98	712	946 (498/448)	662 (469/193)	538 (372/166)
3/1/98		93 (93/0)	75 (75/0)	58 (58/0)
Totals	1875+	1863 (1123/740)	1416 (1035/381)	1212 (888/324)

[1] West Yellowstone entrances only.

and these values have been converted to gram/mile values for the range of gas mileage of 9 to 15 mpg. These ranges were chosen to span the fuel consumption range between the larger 3-cylinder performance sleds (600 - 700 cc displacements) and the much smaller sport models (340 - 440 cc displacements). The average fuel economy for the two snowmobiles (1998 Polaris Indy Trail, 488cc fan-cooled and a 1996 Polaris Indy Wide Track LX, 488cc liquid cooled) used to transport the equipment and personnel through the park during the week of work was 13 mpg.

Previous emissions measurements of snowmobiles is limited. Dynamometer work carried out by Southwest Research on two snowmobile engines (a 1997 488cc Fan cooled engine from Polaris and a 1995 440cc liquid cooled Artic Cat engine) provide the only measurements which can be directly compare with this work (2). Using an engine dynamometer a 5-mode steady-state test was run on these engines using various fuels (gasoline, gasohol and Aliphatic) and lubes at room temperature (~70° F). Emissions ranges of 2299 - 2557 gCO/gal and 723 - 1028 gHC/gal were reported for the Polaris engine. Emissions ranges of 1856 - 2040 gCO/gal and 833 - 918 gHC/gal for the Artic Cat engine. The CO emissions reported by Southwest Research are a factor of two higher than we observed at the park entrance while the HC emissions are similar. The tests conducted by Southwest Research were made with intake air temperature of 70°F compared with 0° - 15°F for the measurements at park entrance. The increased air density which accompanies the lower temperature alone can account for the decreases in CO emissions observed at the park entrance. HC emissions, since they are dominated by non-combustion sources should be largely unaffected by air density changes. Changes in air density may also contribute to the differences observed between the morning and afternoon measurements and indicates that future emissions measurements need to include temperature measurements.

Table II. Summary of Emissions Measurements with Valid CO & HC.

Measurement Period (# records)	Mean %CO (Median)	Mean %HC (Median)	gCO/gal[1] (gCO/mile)[2]	gHC/gal[1] (gHC/mile)[2]
Mornings (888)	5.16% (5.10%)	2.74% (2.70%)	1151 (128 - 77)	956 (106 - 64)
Afternoons (324)	6.62% (6.61%)	2.14% (2.06%)	1569 (174 - 105)	779 (87 - 52)
Totals (1212)	5.55% (5.59%)	2.58% (2.56%)	1262 (140 - 84)	909 (101 - 61)

[1] Assumes a fuel density of 0.726 g/ml.
[2] Assumes a gas mileage of range of 9 to 15 mpg.

The emissions data are normally distributed (means and median are approximately equal) for both CO and HC. Figure 1 shows this for CO. This is in sharp contrast to automobile emissions (even older models without emissions control equipment) where these emissions are gamma distributed (the median is much lower than the mean). The dramatic differences can be seen in the comparison between the decile plots shown in Figures 2 and 3. Figure 2 is for the normally distributed snowmobiles and Figure 3 for the gamma distributed on-road vehicle fleet measured in Denver in 1995/1996 (3,4). The normal distribution may likely be rooted in the fact that 2-stroke engines have a limited operational range which is not greatly impacted by maintenance habits which can dramatically affect emissions from automobiles.

For comparison purposes a few measurements were collected on winter transportation vehicles other than snowmobiles. One Ford Econoline conversion snow coach (0.42 %CO, 155 gCO/gal, -0.098 %HC) and one Bombardier snow coach (2.88 %CO, 972 gCO/gal, 0.15 %HC, 80 gHC/gal) were measured on 3/2/97. The negative value measured on the Ford Econoline van does not mean it is cleaning the air, but that a very low reading was recorded which was negatively impacted by instrument noise or perhaps the environmental conditions. The emission values obtained from the Bombardier snow coach are typical of a modern 4-stroke gasoline engine with no emissions control equipment.

A still frame video picture of each snowmobile measurement was recorded on video tape for later review. These tapes were transcribed for make, model and engine displacement where possible. Engine displacement was inferred from make and model information obtained from the manufacturers for their 1997 models. The West Yellowstone rental fleet is composed

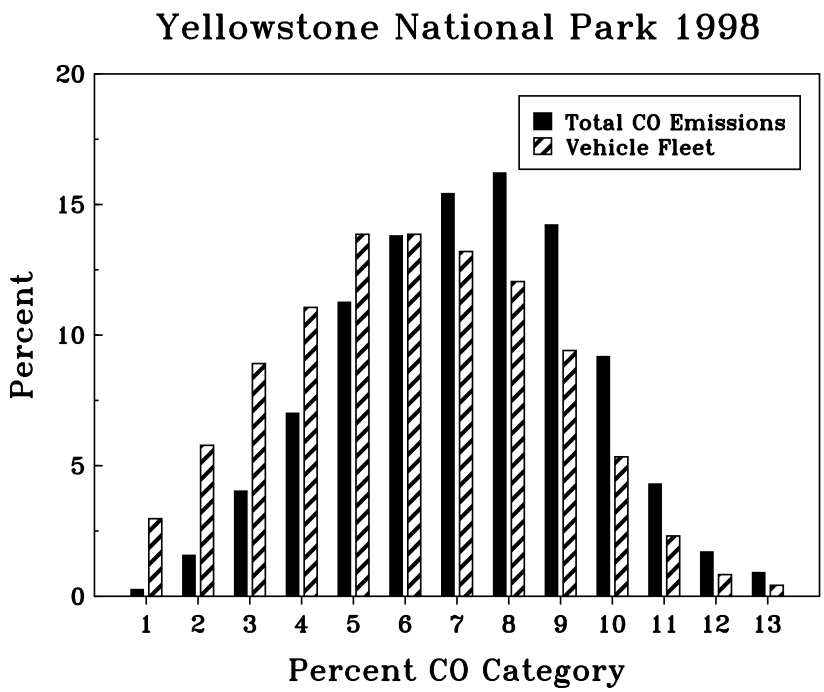

Figure 1. Percent of snowmobile fleet and the total CO emissions for all valid CO and HC measurements (1212 sleds). The upper boundary of each bin defined as <= %CO.

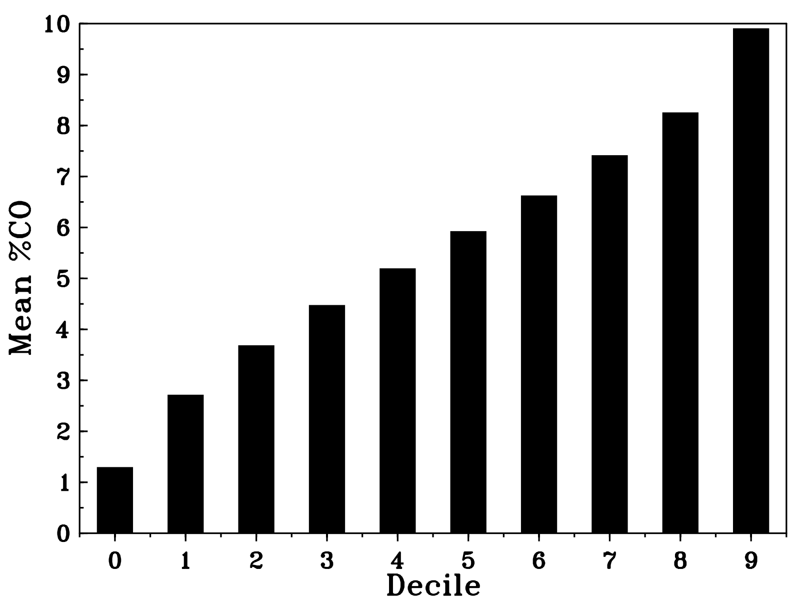

Figure 2. Mean %CO emissions by decile for all valid CO and HC measurements (1212 sleds) collected at the W. Yellowstone entrance to Yellowstone National Park.

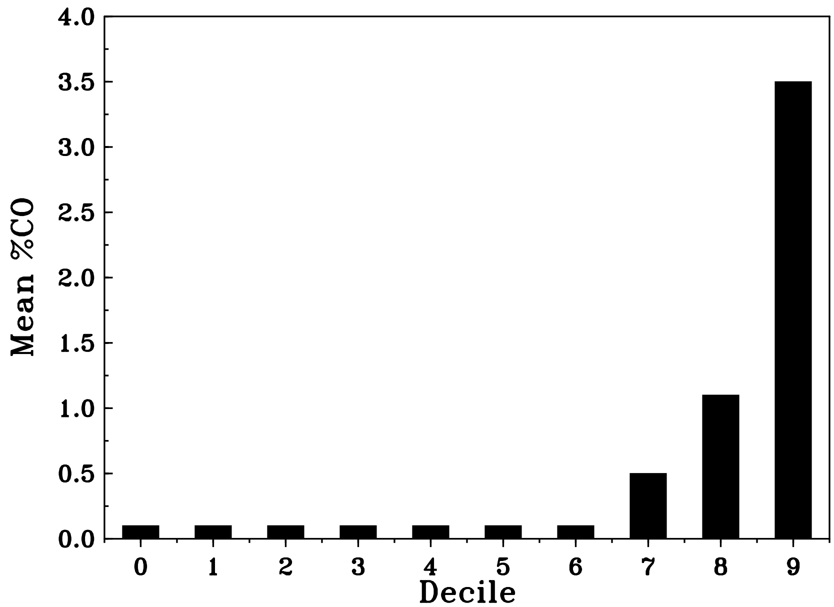

Figure 3. Mean %CO emissions by decile for 19,011 on-road vehicles measured in Denver, CO. in December, 1995 and January, 1996 (4).

mainly of the newer models each year, however, the engine displacement information will be subject to potential errors for older sled.

Figure 4 shows the distribution of makes for the morning data for the four manufacturers. Out of the 888 snowmobiles which entered the park during the morning 849 could be identified from the video tapes for make. Only 805 of the sleds could be identified for engine cooling type. Figure 5 shows the distribution by engine size (assuming that the identified sleds were all 1997 models). Figure 6 gives the mean CO and HC emissions by manufacturer and engine cooling type. The error bars are reported as the standard error of the mean.

System limitations of the standard on-road system were explored during all of the testing. One limitation is the inability of the system to tolerate snow spray which is kicked up behind the sleds. The software restricts the amount of noise which the data can contain and still report a valid measurement. This limits measurements to low speeds, such as at the entrance gates, or requires a means to reduce or eliminate loose snow. One additional measurement location might be in the thermal areas where the roadways are covered with wood chips.

A second limitation may account for the differences observed in the HC emissions between the fan cooled engines and the liquid cooled engines. The HC channel in the remote sensor can be positively interfered with by liquid water vapor (steam) and report this interference as HC emissions. While the liquid cooled sleds were not observed to emit steam at the exhaust pipe there is often a large amount of steam emitted off of the sleds running boards. The running boards serve as the cooling systems heat exchangers on the liquid cooled sleds and

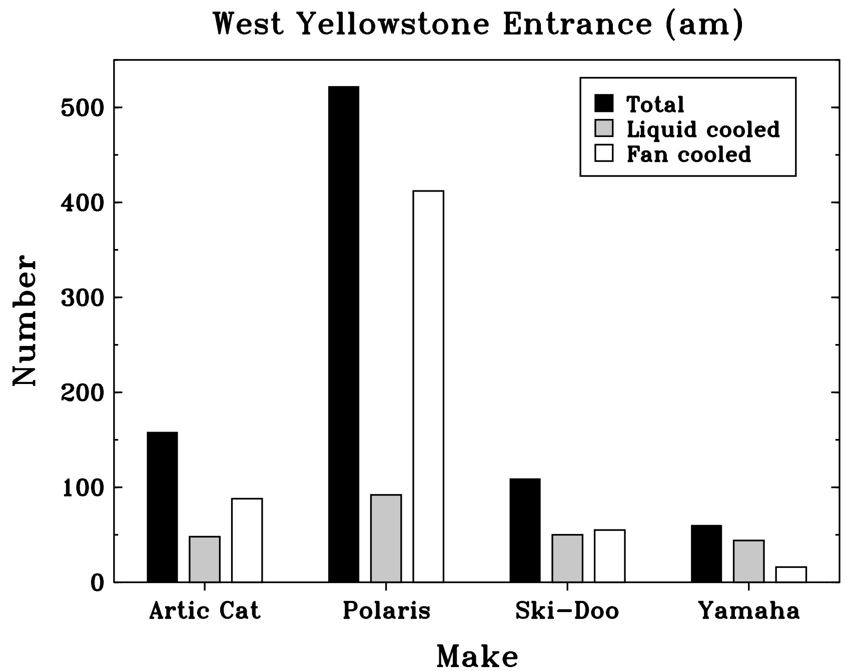

Figure 4. Frequency by make and cooling type among emission measured snowmobiles entering Yellowstone National Park at the West Yellowstone entrance.

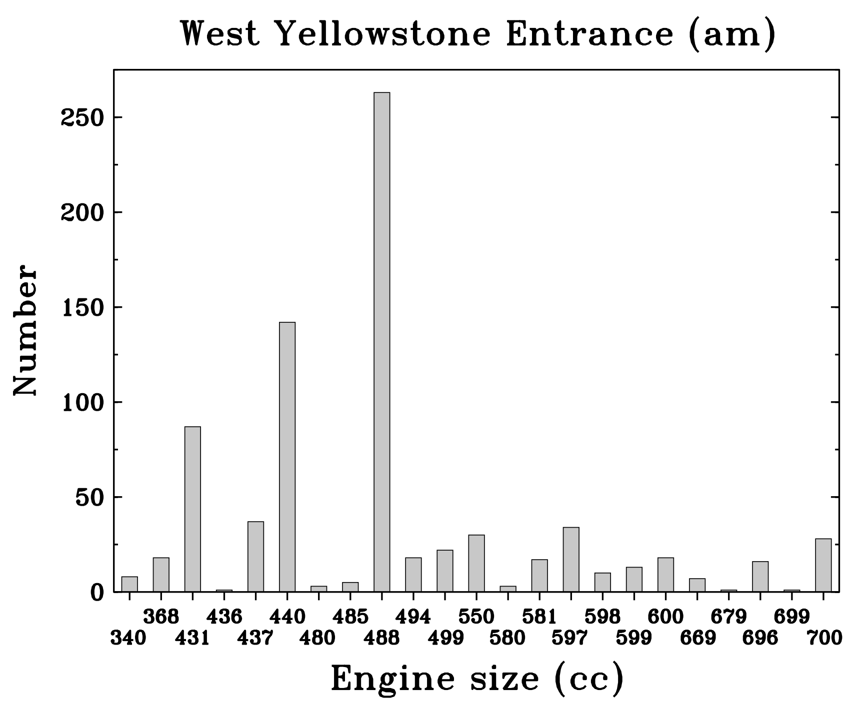

Figure 5. Frequency of snowmobile engine size (assuming 1997 model sleds) among emission measured snowmobiles entering Yellowstone National Park at the West Yellowstone entrance.

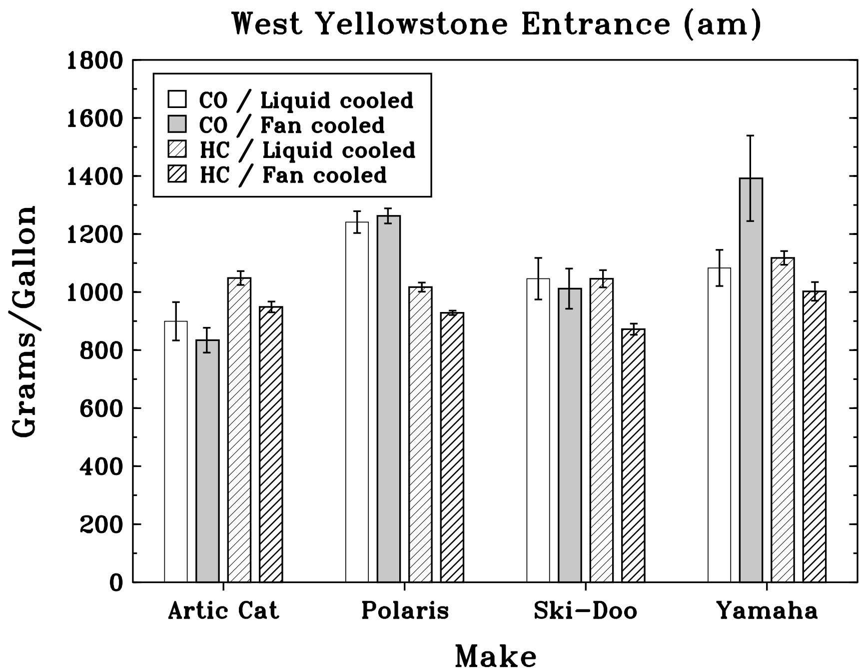

Figure 6. Measured CO and HC g/gal emissions by make and engine cooling type for morning snowmobile entrances to Yellowstone National Park at the West Yellowstone entrance.

snow which is kicked up on the underneath side of the running board often produces a "steam" cloud which is then entrained with the exhaust as the sled moves forward. It is therefore possible that the higher HC emissions observed from the liquid cooled sleds could be the result of a positive water interference during the measurement.

It was beyond the scope of this work to attempt to evaluate the impact on emissions that the use of oxygenated fuels may be having. While many of the rental companies in West Yellowstone are using the fuel in their rental sleds there are still many fuel sources inside and outside the park which are not selling the fuel. The observed difference in CO emissions in the morning and afternoon may be a result of fuel changes, but is just as likely to be a result of the sampling bias which was introduced by the software and its intolerance of snow spray. Air density changes caused by warmer afternoon temperatures could also be a contributing factor.

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References

1. Bishop, G. A.; Stedman, D. H. *Acc. Chem. Res.* **1996**, *29*, 489-495.

2. White, J. J.; Carroll, J. N.; Haines, H. E. *Soc. Auto. Eng.* **1997**, *972108*.

3. Zhang, Y.; Bishop, G. A.; Stedman, D. H. *Environ. Sci. & Technol.* **1994**, *28*, 1370-1374.

4. Stedman, D.H.; Bishop, G.A.; Aldrete, P.; Slott, R.S. *Environ. Sci. & Technol.* **1997**, *31*, 927-931.

Appendix B:

Photographs of Sites and Instrumentation

Photograph 1. The West Entrance of Yellowstone National Park. The snowmobiles are in the Express Lane where the emission measurements were collected. To the left of the Express Lane is the West Exit, the site for afternoon measurements.

Photograph 2. Instrumentation setup in the Express Lane of the West Entrance. On the left side is the detector and to the right is the IR/UV source.

Photograph 3. Yellowstone visitors exiting the park at the West Exit. The IR/UV source on the left and the detector on the right.

Photograph 4. The South Entrance into Yellowstone National Park. The IR/UV source and detector are again present in the picture.

Appendix C:

Data from Method 2: 1999

1999 Polaris Sport

Ethanol Measurements						Non-oxygenated Measurements					
date	time	co/co2	hc/co2	%CO	%HC	date	time	co/co2	hc/co2	%CO	%HC
2/14/99	10:44	0.604	0.231	6.26	2.39	2/17/99	12:34	0.451	0.110	5.06	1.23
2/14/99	10:44	0.425	0.197	4.84	2.24	2/17/99	12:34	0.465	0.159	5.16	1.77
2/14/99	10:45	0.674	0.165	6.79	1.66	2/17/99	12:35	0.512	0.110	5.57	1.20
2/14/99	10:45	0.546	0.154	5.86	1.65	2/17/99	12:36	0.504	0.210	5.45	2.27
2/14/99	10:46	0.615	0.153	6.39	1.59	2/17/99	12:36	0.396	0.070	4.61	0.82
2/14/99	10:46	0.634	0.141	6.53	1.45	2/17/99	12:37	0.493	0.155	5.39	1.70
2/14/99	10:46	0.920	0.218	8.27	1.96	2/17/99	12:38	0.536	0.161	5.73	1.72
2/14/99	10:47	0.824	0.190	7.73	1.78	2/17/99	12:39	0.554	0.150	5.88	1.59
2/14/99	10:48	0.677	0.162	6.82	1.64	2/17/99	12:39	0.489	0.071	5.41	0.78
2/14/99	10:48	0.667	0.158	6.75	1.60	2/17/99	12:40	0.687	0.109	6.85	1.09
2/14/99	10:48	0.528	0.192	5.70	2.07	2/17/99	12:40	0.594	0.111	6.20	1.16
2/14/99	10:49	0.561	0.128	6.00	1.37	2/17/99	12:41	0.544	0.131	5.81	1.39
2/14/99	10:49	0.546	0.155	5.86	1.66	2/17/99	12:42	1.107	0.108	9.21	0.90
2/14/99	10:50	0.859	0.176	7.95	1.63	2/17/99	12:42	0.691	0.119	6.87	1.18
2/14/99	10:52	0.696	0.159	6.94	1.59	2/17/99	12:43	0.471	0.149	5.21	1.65
2/14/99	10:53	0.567	0.128	6.04	1.36	2/17/99	12:44	0.491	0.137	5.38	1.51
2/14/99	10:53	0.526	0.139	5.71	1.52	2/17/99	12:44	0.381	0.130	4.44	1.51
2/14/99	10:54	0.867	0.223	7.97	2.05	2/17/99	12:45	0.538	0.151	5.75	1.61
2/14/99	10:54	0.705	0.157	7.00	1.56	2/17/99	12:45	0.601	0.199	6.20	2.05
2/14/99	10:55	0.920	0.189	8.29	1.70	2/17/99	12:46	0.684	0.164	6.80	1.63
2/14/99	10:55	0.532	0.163	5.75	1.76	2/17/99	12:47	0.699	0.141	6.91	1.40
2/14/99	10:56	0.838	0.182	7.82	1.69	2/17/99	12:47	0.408	0.229	4.63	2.60
2/14/99	10:56	0.836	0.181	7.81	1.69	2/17/99	12:48	0.599	0.161	6.20	1.67
2/14/99	10:57	0.579	0.143	6.13	1.51	2/17/99	12:49	0.525	0.124	5.67	1.34
2/14/99	10:57	1.158	0.269	9.42	2.19	2/17/99	12:50	0.743	0.189	7.17	1.83
2/14/99	10:58	1.157	0.242	9.43	1.97	2/17/99	12:50	0.695	0.180	6.86	1.77
2/14/99	10:58	0.723	0.143	7.13	1.41	2/17/99	12:51	0.655	0.132	6.62	1.33
2/14/99	10:59	0.657	0.129	6.70	1.31	2/17/99	12:51	0.484	0.231	5.28	2.51
2/14/99	10:59	0.695	0.142	6.95	1.42	2/17/99	12:52	0.764	0.156	7.32	1.49
2/14/99	10:59	0.576	0.138	6.10	1.46	2/17/99	12:53	1.087	0.120	9.11	1.00

1996 Polaris Lite GT

Ethanol Measurements

date	time	co/co2	hc/co2	%CO	%HC
2/14/99	11:01	0.313	0.131	3.82	1.60
2/14/99	11:03	0.548	0.127	5.90	1.37
2/14/99	11:03	0.805	0.162	7.64	1.54
2/14/99	11:04	0.655	0.135	6.68	1.38
2/14/99	11:04	0.796	0.142	7.60	1.35
2/14/99	11:22	0.489	0.133	5.42	1.47
2/14/99	11:23	0.649	0.143	6.63	1.46
2/14/99	11:24	0.602	0.129	6.30	1.35
2/14/99	11:25	0.753	0.177	7.31	1.72
2/14/99	11:25	0.742	0.134	7.27	1.31
2/14/99	11:26	0.752	0.142	7.33	1.38
2/14/99	11:26	0.550	0.125	5.91	1.34
2/14/99	11:27	0.534	0.124	5.79	1.34
2/14/99	11:27	0.728	0.129	7.18	1.27
2/14/99	11:28	0.603	0.132	6.31	1.38
2/14/99	11:28	1.596	0.486	10.96	3.34
2/14/99	11:28	0.492	0.124	5.45	1.37
2/14/99	11:29	0.608	0.131	6.34	1.37
2/14/99	11:29	0.515	0.156	5.62	1.70
2/14/99	11:30	0.617	0.104	6.43	1.09
2/14/99	11:30	0.576	0.124	6.11	1.31
2/14/99	11:31	0.560	0.141	5.98	1.50
2/14/99	11:31	0.728	0.136	7.18	1.34
2/14/99	11:32	0.694	0.169	6.92	1.69
2/14/99	11:32	0.722	0.156	7.12	1.54
2/14/99	11:33	0.651	0.160	6.64	1.64
2/14/99	11:33	0.608	0.116	6.36	1.21
2/14/99	11:34	0.724	0.152	7.13	1.50
2/14/99	11:34	0.849	0.148	7.91	1.38
2/14/99	11:35	0.886	0.146	8.12	1.34
2/14/99	11:35	0.709	0.145	7.04	1.44
2/14/99	11:36	0.634	0.129	6.54	1.33
2/14/99	11:36	0.460	0.122	5.19	1.37

Non-Oxygentated Measurements

date	time	co/co2	hc/co2	%CO	%HC
2/17/99	12:04	0.236	0.152	2.98	1.91
2/17/99	12:05	0.576	0.128	6.05	1.34
2/17/99	12:05	0.491	0.089	5.42	0.98
2/17/99	12:06	0.632	0.196	6.42	1.99
2/17/99	12:07	0.680	0.165	6.77	1.64
2/17/99	12:07	0.381	0.095	4.45	1.11
2/17/99	12:08	0.468	0.248	5.13	2.72
2/17/99	12:09	0.769	0.125	7.37	1.20
2/17/99	12:10	0.643	0.181	6.51	1.83
2/17/99	12:10	0.578	0.216	6.01	2.25
2/17/99	12:11	0.658	0.118	6.65	1.19
2/17/99	12:11	0.879	0.215	7.96	1.95
2/17/99	12:12	0.554	0.243	5.82	2.56
2/17/99	12:13	0.674	0.211	6.70	2.09
2/17/99	12:13	0.628	0.218	6.38	2.22
2/17/99	12:14	0.870	0.175	7.94	1.59
2/17/99	12:15	0.488	0.196	5.32	2.14
2/17/99	12:15	0.826	0.098	7.74	0.92
2/17/99	12:16	0.825	0.124	7.71	1.16
2/17/99	12:17	0.818	0.279	7.56	2.58
2/17/99	12:17	1.120	0.198	9.20	1.63
2/17/99	12:18	0.412	0.099	4.74	1.13
2/17/99	12:18	1.021	0.169	8.74	1.45
2/17/99	12:19	0.935	0.172	8.30	1.52
2/17/99	12:20	0.898	0.181	8.09	1.63
2/17/99	12:23	0.609	0.213	6.24	2.18
2/17/99	12:24	0.814	0.199	7.59	1.86
2/17/99	12:25	0.783	0.178	7.42	1.69
2/17/99	12:26	0.476	0.072	5.30	0.80
2/17/99	12:27	0.395	0.218	4.52	2.50

1984 Arctic Cat Panther

Ethanol Measurements

		co/co2	hc/co2	%CO	%HC
2/10/99	11:04	0.626	0.118	6.49	1.22
2/10/99	11:05	0.660	0.130	6.72	1.32
2/10/99	11:06	0.448	0.132	5.07	1.49
2/10/99	11:07	0.486	0.105	5.41	1.17
2/10/99	11:07	0.764	0.129	7.41	1.25
2/10/99	11:08	0.706	0.118	7.04	1.17
2/10/99	11:09	0.878	0.136	8.09	1.25
2/10/99	11:09	0.807	0.139	7.67	1.32
2/10/99	11:10	0.789	0.123	7.57	1.18
2/10/99	11:12	0.723	0.161	7.13	1.58
2/10/99	11:13	0.908	0.161	8.24	1.46
2/10/99	11:14	0.829	0.182	7.77	1.71
2/10/99	11:16	0.885	0.172	8.10	1.57
2/10/99	11:17	0.879	0.163	8.07	1.50
2/10/99	11:17	0.870	0.138	8.04	1.28
2/10/99	11:18	0.859	0.174	7.95	1.61
2/10/99	11:19	0.852	0.131	7.94	1.22
2/10/99	11:19	0.870	0.151	8.03	1.39
2/10/99	11:20	0.856	0.121	7.97	1.13
2/10/99	11:21	0.915	0.164	8.28	1.48
2/10/99	11:21	0.895	0.161	8.17	1.47
2/10/99	11:22	0.876	0.140	8.07	1.29
2/10/99	11:23	0.847	0.212	7.85	1.97
2/10/99	11:23	0.797	0.135	7.61	1.29
2/10/99	11:24	0.915	0.143	8.29	1.29
2/10/99	11:25	0.859	0.139	7.97	1.29
2/10/99	11:26	0.655	0.113	6.70	1.15
2/10/99	11:26	0.734	0.121	7.22	1.19
2/10/99	11:27	0.861	0.178	7.96	1.65
2/10/99	11:28	0.905	0.129	8.24	1.18
2/10/99	11:30	0.961	0.272	8.45	2.39
2/10/99	11:31	1.006	0.253	8.70	2.19
2/10/99	11:32	1.058	0.172	9.01	1.47
2/10/99	11:33	0.789	0.139	7.56	1.34
2/10/99	11:33	0.862	0.197	7.95	1.82
2/10/99	11:34	1.084	0.164	9.14	1.38
2/10/99	11:35	0.630	0.177	6.48	1.82
2/10/99	11:37	0.780	0.131	7.51	1.26
2/10/99	11:38	0.754	0.175	7.32	1.70
2/10/99	11:39	0.739	0.164	7.22	1.60
2/10/99	11:40	0.930	0.264	8.29	2.35

Non-oxygenated Measurements

		co/co2	hc/co2	%CO	%HC
2/17/99	11:21	1.015	0.348	8.58	2.94
2/17/99	11:24	1.514	0.458	10.58	3.20
2/17/99	11:25	1.569	0.401	10.81	2.76
2/17/99	11:26	1.619	0.461	10.93	3.11
2/17/99	11:26	1.598	0.420	10.89	2.86
2/17/99	11:27	1.704	0.572	11.12	3.73
2/17/99	11:28	1.596	0.403	10.90	2.75
2/17/99	11:28	1.539	0.295	10.79	2.07
2/17/99	11:29	1.218	0.263	9.59	2.07
2/17/99	11:30	1.605	0.353	10.96	2.41
2/17/99	11:30	1.699	0.443	11.19	2.92
2/17/99	11:31	1.423	0.303	10.37	2.21
2/17/99	11:31	1.480	0.298	10.58	2.13
2/17/99	11:32	1.093	0.224	9.05	1.86
2/17/99	11:32	1.257	0.229	9.78	1.78
2/17/99	11:33	1.012	0.248	8.64	2.11
2/17/99	11:33	0.933	0.126	8.32	1.12
2/17/99	11:34	1.098	0.230	9.07	1.90
2/17/99	11:35	1.184	0.209	9.48	1.67
2/17/99	11:35	1.270	0.238	9.82	1.84
2/17/99	11:36	1.335	0.246	10.08	1.86
2/17/99	11:36	1.210	0.228	9.58	1.80
2/17/99	11:37	1.236	0.203	9.71	1.59
2/17/99	11:37	1.281	0.235	9.87	1.81
2/17/99	11:38	1.251	0.241	9.74	1.88
2/17/99	11:39	1.416	0.411	10.26	2.98
2/17/99	11:39	1.236	0.251	9.67	1.96
2/17/99	11:40	1.568	0.322	10.86	2.23
2/17/99	11:41	1.357	0.265	10.15	1.98
2/17/99	11:41	1.180	0.230	9.44	1.84
2/17/99	11:42	0.877	0.214	7.95	1.94

Appendix D:

Data from Method 3: 1999

1999 Ski-Doo Rotax 600 DPM

Ethanol Measurements - Snowmobile A

date	time	co/co2	hc/co2	%CO	%HC
2/18/99	13:33	0.701	0.210	6.95	2.09
2/18/99	13:34	0.549	0.169	5.88	1.81
2/18/99	13:35	0.504	0.320	5.44	3.46
2/18/99	13:35	0.516	0.163	5.62	1.77
2/18/99	13:35	0.673	0.111	6.82	1.12
2/18/99	13:36	0.565	0.174	6.00	1.85
2/18/99	13:36	0.594	0.212	6.19	2.22
2/18/99	13:36	0.515	0.173	5.61	1.88
2/18/99	13:36	0.614	0.223	6.33	2.30
2/18/99	13:37	0.620	0.152	6.42	1.58
2/18/99	13:37	0.528	0.197	5.70	2.13
2/18/99	13:37	0.674	0.126	6.82	1.27
2/18/99	13:37	0.704	0.229	6.96	2.26
2/18/99	13:38	0.765	0.222	7.35	2.14
2/18/99	13:38	0.653	0.222	6.62	2.25
2/18/99	13:38	0.740	0.142	7.24	1.39
2/18/99	13:38	0.622	0.178	6.42	1.84
2/18/99	13:39	0.656	0.142	6.68	1.45
2/18/99	13:39	0.574	0.254	6.03	2.67
2/18/99	13:39	0.860	0.177	7.96	1.64
2/18/99	13:39	0.687	0.208	6.86	2.07
2/18/99	13:40	0.737	0.196	7.19	1.91
2/18/99	13:40	0.631	0.175	6.49	1.80
2/18/99	13:40	0.950	0.316	8.36	2.78
2/18/99	13:41	0.591	0.204	6.18	2.13
2/18/99	13:41	0.728	0.165	7.15	1.62
2/18/99	13:42	1.090	0.427	8.99	3.52
2/18/99	13:42	0.700	0.238	6.92	2.36
2/18/99	13:42	0.771	0.184	7.41	1.77
2/18/99	13:43	0.688	0.235	6.84	2.34
2/18/99	13:43	0.666	0.183	6.73	1.85

Non-oxygenated Measurements - Snowmobile B

date	time	co/co2	hc/co2	%CO	%HC
2/18/99	13:33	0.711	0.112	7.01	1.11
2/18/99	13:33	0.910	0.204	8.14	1.82
2/18/99	13:34	0.584	0.151	6.10	1.58
2/18/99	13:35	0.696	0.428	6.70	4.12
2/18/99	13:35	0.831	0.233	7.67	2.15
2/18/99	13:35	0.679	0.301	6.67	2.96
2/18/99	13:36	0.826	0.351	7.56	3.21
2/18/99	13:36	0.754	0.180	7.24	1.73
2/18/99	13:36	0.688	0.264	6.75	2.60
2/18/99	13:37	0.900	0.199	8.09	1.79
2/18/99	13:37	0.696	0.287	6.80	2.80
2/18/99	13:37	0.904	0.199	8.11	1.79
2/18/99	13:37	0.712	0.229	6.94	2.23
2/18/99	13:38	0.753	0.208	7.21	2.00
2/18/99	13:38	0.685	0.218	6.77	2.15
2/18/99	13:38	0.936	0.210	8.28	1.86
2/18/99	13:38	0.652	0.237	6.53	2.37
2/18/99	13:39	1.099	0.193	9.11	1.60
2/18/99	13:39	0.739	0.224	7.12	2.15
2/18/99	13:39	1.023	0.275	8.68	2.34
2/18/99	13:39	0.684	0.223	6.76	2.21
2/18/99	13:40	1.069	0.238	8.93	1.99
2/18/99	13:40	0.790	0.230	7.43	2.16
2/18/99	13:40	0.664	0.246	6.61	2.45
2/18/99	13:40	1.002	0.238	8.60	2.05
2/18/99	13:41	0.516	0.190	5.55	2.04
2/18/99	13:41	1.046	0.212	8.84	1.79
2/18/99	13:42	0.765	0.275	7.24	2.60
2/18/99	13:42	1.122	0.224	9.19	1.83
2/18/99	13:42	0.580	0.136	6.08	1.42
2/18/99	13:43	0.865	0.175	7.91	1.60
2/18/99	13:43	0.764	0.300	7.22	2.83
2/18/99	13:43	0.917	0.281	8.12	2.49